Solar activity and Space Weather effects on Earth's upper atmosphere
Analysis of thermospheric density from ESA GOCE mission

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The thermosphere is the layer of the Earth’s upper atmosphere directly above the mesosphere and directly below the exosphere (90–600 km altitude).

The thermosphere, **largely driven by the solar and geomagnetic activity**, shows a strong coupling with the ionosphere and the magnetosphere.

There are about **800** active satellites in Low Earth Orbit and about **29,000 debris** larger than 10 cm.

GOCE Mission and the Thermosphere

• ESA's Gravity field and steady-state Ocean Circulation Explorer (GOCE) was launched on 17 March 2009, mapping Earth's gravity field with unprecedented detail.

• Soon after launch, Mission risked to be aborted for overcompensation of the air drag! (extended QP between cycles 23 and 24)

• The on-board ultra-sensitive accelerometers provided 10 Hz-sampled data and 1 Hz-sampled multi-channel SSTI GPS instrument data.

• Thermospheric densities sampled at 0.1 Hz at 260 km altitude have been computed and made available within the ESA GOCE Archive (01/11/2009 -20/10/2013)

  => A unique Dataset !
GOCE was kept in free-fall at about 250 km for over 4 yrs

Decay rate of the Solar Maximum Mission, which deorbited in December 1989, varied with the Sun’s 27-day rotation and the solar cycle.

Courtesy of Dr. Judith Lean.
GOCE Re-entry Prediction

Figure 101: Final GOCE re-entry prediction of the ESOC Space Debris Office.
Total and spectral solar Irradiance: Solar Cycle modulation

1) **F10.7 index** from Penticton Observatory, Canada;
2) **MgII index** (LASP composite/Bremen Mg II composite);
3) Geomagnetic activity is represented by the planetary **geomagnetic index Ap** (the Ap-index is thus a geomagnetic activity index where days with high levels of activity have a higher daily Ap-value).
Solar UV irradiance at 1 AU (astronomical unit). ASTM E-490 (red) and spectral data of Gueymard. Average solar activity conditions. Mg II (280nm) index is a good proxy of solar facular TSI and UV components (Dudok de Wit et al., 2009).
a) Atmospheric density vs time (both 10 s sampled and daily averaged) during GOCE mission; b) Geomagnetic index ap and daily-averaged geomagnetic index Ap vs time during GOCE mission; c) and d) F10.7 and Mg II cwr vs time during GOCE mission (signal spikes are removed by interpolation). Mg II index seems “cleaner” and less noisy than F10.7.
Dataset and features
EMD reconstruction of thermospheric data
From solar Proxies
Reconstruct GOCE Thermospheric data from proxies

1. **Input data**: daily-averaged thermosphere density $\bar{\rho}$, daily-averaged geomagnetic index Ap and the solar flux indices $F_{10.7}$ and $Mg\ II$.

2. **Phase shifting**: A 9h time delay is assumed for Ap, no time delay for solar indices. A cubic spline interpolation is used for Ap (1d sampling).

3. **EMD sifting process**: applied to GOCE density and activity indices to extract the corresponding IMFs ($IMF_i^{Ap}, IMF_i^{F_{10.7}}, IMF_i^{Mg\ II}$) and trends ($res^{Ap}, res^{F_{10.7}}, res^{Mg\ II}$) that represent the original data vector broken down into frequency components [Huang et al., 1998, Wang et al., 2010].

4. **Thermosphere Density Model(s)**: Iterative data analysis for Ap and solar indices a *weighting factor* and a sub-set of IMFs (including the residual trends) are selected (Exhaustive Monte Carlo Analysis).

Density signals are reconstructed for the whole period during different solar activity levels.
• IMF3 (and 2) are associated to 27-day solar rotation;
• The residual trend shows that MgII index ↑ when solar cycle ↑ because chrom./photosph. ↑
• IMF2-IMF4 are particularly important during the of high solar activity period.
\[ \bar{\rho}_{\text{norm}}^{\text{sim}} = \text{norm}_{(0,1)}\left[ A_p \cdot \text{IMF}_{\text{norm}}^{A_{\text{p}}} + A_{\text{F10.7}} \cdot \text{IMF}_{\text{norm}}^{\text{F10.7}} + A_{\text{MgII}} \cdot \text{IMF}_{\text{norm}}^{\text{MgII}} \right] \]

\[ \sigma_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{n=1}^{N} \left| \bar{\rho}_{\text{norm}}(n) - \bar{\rho}_{\text{norm}}^{\text{sim}}(n) \right|^2} \]

Best-solutions for the analyzed periods.

✓ indicates that the corresponding IMF, labeled from 1 to 10, or the residual trend res is used.
Normalized daily-averaged real and simulated density signal vs time

Cauli et al. KIS Thinkshop on Planetary-stellar connection: The Sun’s Lesson. Freiburg, May 7-9 2018
http://spaceweather.roma2.infn.it

- Del Moro et al., Forecasting the CME propagation with the P-DBM model, Proceedings IAGA Italia Symposium, 2018 in press
- Napoletano et al., A probabilistic approach to the drag-based model, Journal of Space Weather and Space Climate, 8, 25 A11, 2018
Conclusions

- Use of solar proxies is an essential feature in Thermospheric modelling.

- Current models need refinement to predict low-altitude thermospheric densities

- Availability of very low-altitude (GOCE) data further allows stringent model testing at different altitudes.

- Mg II is an important proxy:
  - For medium activity the use of only $Mg\ II$ reproduces density data with a RMS error of 7.4%
  - High solar activity: the best reconstruction combines IMFs from Ap and $Mg\ II$ indices. The RMS error is below 14%. Peaks are well-reproduced.
  - Combined medium and high: the best reconstruction combines IMFs from Ap and $Mg\ II$ indices. The reconstruction presents period of over/under-estimation. The RMS error is about 11%.
  - Secular trends Availability of historical data for Ap, F 10.7 and MgII allows thermospheric density profiles be derived using historical records of MgII, F10.7 and Ap.